



An analysis of changes in temperature extremes in the Three River Headwaters region of the Tibetan Plateau during 1961–2016

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ABSTRACT

Regional spatiotemporal assessments of temperature extremes are essential for accurate forecasting of future climate changes, agricultural production and the regulation of water resources. This study evaluates the characteristics of the spatiotemporal variations in temperature extremes from 1961 to 2016 in the Three River Headwaters (TRH) region and its surroundings in the northeastern portion of the Tibetan Plateau in China. The association of these variations with atmospheric circulation patterns is also investigated. This study selected twenty-six meteorological stations where < 2% of the data are missing and where the data pass quality control and homogeneity tests. Following the Expert Team on Climate Change Detection and Indices (ETCCDI), thirteen extreme temperature indices and two mean temperature indices are analyzed using the Mann-Kendall test and Sen's test; the indices examined here include six warm indices, six cold indices, the diurnal temperature range (DTR) and the annual minimum and maximum temperatures. Pearson correlation analysis is also used to analyze the correlations between the temperature extremes and various atmospheric circulation patterns. The results indicate that the annual minimum and maximum temperatures display significant increasing trends, whereas the DTR displays a significant decreasing trend with a rate of $-0.11^{\circ}\text{C}/\text{decade}$. All of the regional warm indices display significant increasing trends. On the other hand, most of the cold indices show significant decreasing trends, except for the lowest daily minimum temperature (TNn) and the lowest daily maximum temperature (TXn), which show increasing trends. These results are consistent with the trends observed by most global-scale studies. In terms of spatial patterns, most of the stations that display significant trends are located in the central and northwestern portions of the TRH region. On the other hand, all of the extreme indices show weak correlations with altitude, with the exception of the DTR, which displays a significant negative correlation with altitude ($P < 0.01$); moreover, most of the indices are weakly correlated with latitude and longitude. Overall, the winter Arctic Oscillation index (AO), the summer and winter North Atlantic Oscillation index (NAO), and the summer and winter Western Pacific Subtropical High Intensity Index (WPI) display significant relationships with most of the extreme temperature indices, and these circulation patterns contribute to changes in temperature extremes in this region. However, the Southern Oscillation Index (SOI) is not significantly correlated with most of the extreme temperature indices.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) notes that, since 1880, the global climate system has displayed a significant warming trend, and global mean temperatures have increased by 0.85°C (0.65 – 1.06°C), with the warming trend

becoming more evident since the 1950s (IPCC, 2013). Studies have shown that warming of the climate system leads to increases in extreme climate events, and changes in climate extremes have attracted considerable attention (Alexander et al., 2006; Dong et al., 2016; Wang et al., 2013b). One obvious manifestation of climate change is frequent and prolonged periods of extreme high and low temperatures that have

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serious impacts on the ecological environments of different regions, the daily productivity and lives of people and the social economy (Habeeb et al., 2015; IPCC, 2013). For example, increases in the duration and areas affected by cold waves can greatly reduce the yields of crops and cause sharp increases in the electricity consumption of urban residents, whereas summer heat waves cause people physical discomfort, increase the occurrence of cardiovascular disease and even lead to higher death rates, among other effects (Braga et al., 2002; Gronlund et al., 2016; Thornton et al., 2016). Thus, in-depth understanding and studies of the characteristics of changes in temperature extremes have crucial practical significance for the ecological environments of different regions, industrial and agricultural production and the safety of human lives and property. Moreover, such studies can provide scientific references for the prediction of the temporal and spatial trends of extreme climate in the future (Alexander and Arblaster, 2017; Goubanova and Li, 2007).

The extreme temperature events that have occurred at different spatiotemporal scales in recent decades have attracted considerable amounts of attention from scholars worldwide. At the global scale, the research of Alexander et al. (2006) on extreme climate changes confirms that the global warming of the last 50 years has resulted in increases in warm nights and decreases in cold nights in > 70% of regions worldwide. Furthermore, other extreme temperature events also present clear increasing or decreasing trends. On a regional scale, Choi et al. (2009) analyzed extreme temperature events in the Asia-Pacific region and found that they displayed a similar pattern of change. Moreover, consistent results have been found for Russia (Gruza et al., 1999), eastern Europe (Ruml et al., 2017), Canada (Vincent and Mekis, 2006), northwestern Africa (Filahi et al., 2016), Indonesia (Supari et al., 2017), and Australia (Alexander and Arblaster, 2017), among other regions. In addition, a large number of regional studies of extreme climate events have been conducted and have confirmed that, in the context of global warming, most regions display significant increases in extreme high-temperature days and significant decreases in extreme low-temperature days. Furthermore, because the natural geographical environment and the effects of atmospheric circulation patterns vary among regions, the responses to extreme temperature changes also differ among regions; thus, the characteristics of extreme temperature changes in different regions display notable differences (Lewis and King, 2017). Consistent with the rest of the world, China has experienced significant temperature changes in recent decades (You et al., 2010). During the past 50 years, the average rate of surface temperature increase in China has been 0.27 °C/decade (You et al., 2010), significantly higher than the average rate of warming at the global scale (0.20 °C/decade) or in the Northern Hemisphere (0.24 °C/decade). The extreme temperature changes in China largely follow the same patterns as the global trend; however, due to the complex and diverse topography and the complex and changeable monsoon circulation background, the extreme temperature events in each district display unique distribution patterns and evolution trends (Hu et al., 2016). For example, the variation in extreme temperature events in northern China is significantly higher than that in other regions (Ren and Zhou, 2014; You et al., 2010). Moreover, the extreme temperature events in the Yangtze River basin (Tian and Yang, 2017), northeastern China (Yu and Li, 2015), the Loess Plateau (Sun et al., 2016), arid northwestern China (Chen et al., 2014; Deng et al., 2014), the Tibetan Plateau (You et al., 2008a), and southwestern China (Li et al., 2012b) differ from the overall average trend in China, indicating that the temperature extreme response to global warming is heterogeneous among different regions in China.

The Three River Headwaters (TRH) region is located in the hinterlands of the Tibetan Plateau, which is known as the “Third Pole” of the world. The TRH region features complex topography, high terrain and a harsh climate. It contains vulnerable ecological environments and is sensitive to climate change. During the past two decades, extensive studies have been conducted to investigate climate changes in the TRH region and have found that the TRH region has undergone extreme

changes in the context of global climate change. However, because the TRH region supplies water to the Yellow, Yangtze and Lancang Rivers in China, studies on extreme climate events in this region have concentrated mainly on extreme precipitation events (Cao and Pan, 2014; Liang et al., 2013; Shi et al., 2016), whereas only a few studies have examined temperature extremes (Liang et al., 2013). Because different researchers have chosen to use various numbers of weather stations and to examine different periods of time, it is difficult to form a clear and systematic understanding of extreme temperature changes in the TRH region. Moreover, as time progresses and climate data accumulate, the changes in extreme temperature events should be studied further.

Therefore, the objective of this study is to quantify the changes in temperature extremes from 1961 to 2016 within the TRH region using a dataset consisting of daily records from 26 meteorological stations. In this investigation, indices of climate extremes generated by the Expert Team on Climate Change Detection and Indices (ETCCDI; http://etccdi.pacificclimate.org/list_27_indices.shtml) of the Commission for Climatology (CCI)/Climate Variability and Predictability (CLIVAR)/Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) are used. We discuss the spatial and temporal variability in the changes in these indices. Furthermore, we compare the differences in the magnitudes of the trends in the temperature extremes and analyze the correlation coefficients obtained for the regionally averaged temperature extremes and the characteristics of the associated changes. Finally, the correlation coefficients between the temperature extremes and large-scale atmospheric circulation patterns are discussed.

2. Materials and methods

2.1. Study area

The “Three River Headwaters” (TRH) region, which contains the headwaters of the Yellow River, the Yangtze River, and the Lancang River, is located in the hinterlands of the Tibetan Plateau (31°39′~36°28′N and 89°42′~102°23′E) (Fig. 1). The TRH region covers an area of $35.66 \times 10^4 \text{ km}^2$, and the elevation of the region as a whole varies between 2500 m and 6900 m, with a mean elevation of over 4000 m (Shi et al., 2016). The study area is a typical plateau continental monsoon region, and it experiences dry and wet seasons. The annual mean temperature ranges from −5.38 °C to 4.14 °C. The annual precipitation ranges from 262.2 to 772.8 mm, of which > 80% occurs during the wet season from May to October (Liang et al., 2013), and the annual evapotranspiration ranges from 730 to 1700 mm.

2.2. Data sources

In total, there are 36 surface meteorological stations in the TRH region. To analyze the temperature extremes, rather strict criteria are applied in the process of selecting station data. These criteria are as follows: (i) a month is considered to have sufficiently complete data if there are 5 or fewer missing days; (ii) a year is considered to be complete if all of the months are complete according to item (i); and (iii) a station is considered to have complete data if the entire record has 5 or fewer missing years according to (ii) (Chu et al., 2010; Limsakul and Singhruck, 2016). Based on these criteria, a total of 26 stations are selected. Overall, the percentage of missing data was lower than 2%, and 22 of these stations do not have any missing values. The initial daily minimum and maximum air temperatures from January 1961 to February 2017 measured at these stations were obtained from the China Meteorological Administration.

2.3. Calculation of the indices

Before the indices are calculated, a quality control step (including a test for outliers and a time consistency test) is carried out using the

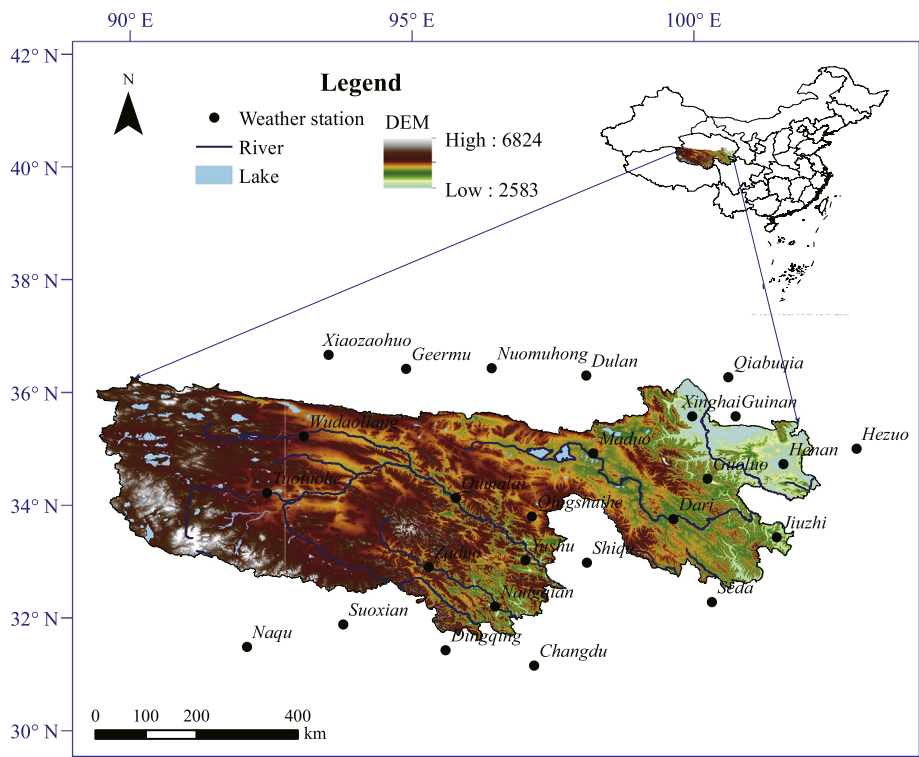


Fig. 1. Locations within the study area and the distribution of meteorological stations.

Table 1
Temperature and precipitation indices selected for this study.

Number	Index	Descriptive name	Definition	Unit
a	TXam	Annual mean TX	Arithmetic mean of the monthly mean values of TX	°C
b	TNam	Annual mean TN	Arithmetic mean of the monthly mean values of TN	°C
1	DTR	Diurnal temperature range	Mean difference between TX and TN	°C
Warm temperature extremes				
2	SU	Summer days	Annual count when TX (daily maximum) > 25 °C	Days
3	TXx	Highest Tmax	Monthly highest TX	°C
4	TNx	Highest Tmin	Monthly highest TN	°C
5	TX90p	Warm days	Number of days when TX > 90th percentile for 1961–2016	Days
6	TN90p	Warm nights	Number of days when TN > 90th percentile for 1961–2016	Days
7	GSL	Growing season length	Annual count between the first span of at least 6 days with TG > 5 °C and the first span of at least 6 days with TG < 5 °C in the second half of the year	Days
Cold temperature extremes				
8	ID	Ice days	Annual number of days when TX < 0 °C	Days
9	TNn	Lowest Tmin	Monthly lowest TN	°C
10	TXn	Lowest Tmax	Monthly lowest TX	°C
11	TX10p	Cold days	Number of days when TX < 10th percentile for 1961–2016	Days
12	TN10p	Cold nights	Number of days when TN < 10th percentile for 1961–2016	Days
13	FD	Frost days	Annual number of days when TN < 0 °C	Days

RClimDex software package (<http://etccdi.pacificclimate.org/software.shtml>) developed by (Zhang and Yang, 2004). To comprehensively assess the temperature changes of the past 56 years in the TRH region, we select 15 temperature indices, including 13 extreme indices and the monthly mean values of the daily maximum and minimum temperatures (Table 1); all of the indices are calculated in RClimDex (Supari et al., 2017; Wang et al., 2017). Moreover, to facilitate comparisons with other studies, the threshold values of these indices are set to the default values used in the software package. The extreme indices used in this study are divided into 3 types (Klein Tank and Können, 2003; Wang et al., 2017). The warm temperature extreme indices are the number of summer days (SU), the highest daily maximum and minimum temperatures (TXx and TNx), the numbers of warm days and nights (TX90p and TN90p) and the growing season length (GSL). The

cold temperature extreme indices are the number of ice days (ID), the lowest daily maximum and minimum temperatures (TXn and TNn), the numbers of cold days and nights (TX10p and TN10p) and the number of frost days (FD). The third type includes the annual mean maximum and minimum temperatures (TXam and TNam) and the diurnal temperature range (DTR).

2.4. Methods

2.4.1. Mann-Kendall test for monotonic trends

The nonparametric Mann-Kendall (MK) test recommended by the WMO has been used to calculate the level of significance of trends (Kendall, 1975; Ma et al., 2015; Mann, 1945), and it is widely applied to detect monotonic trends in time series of hydrological and climatic

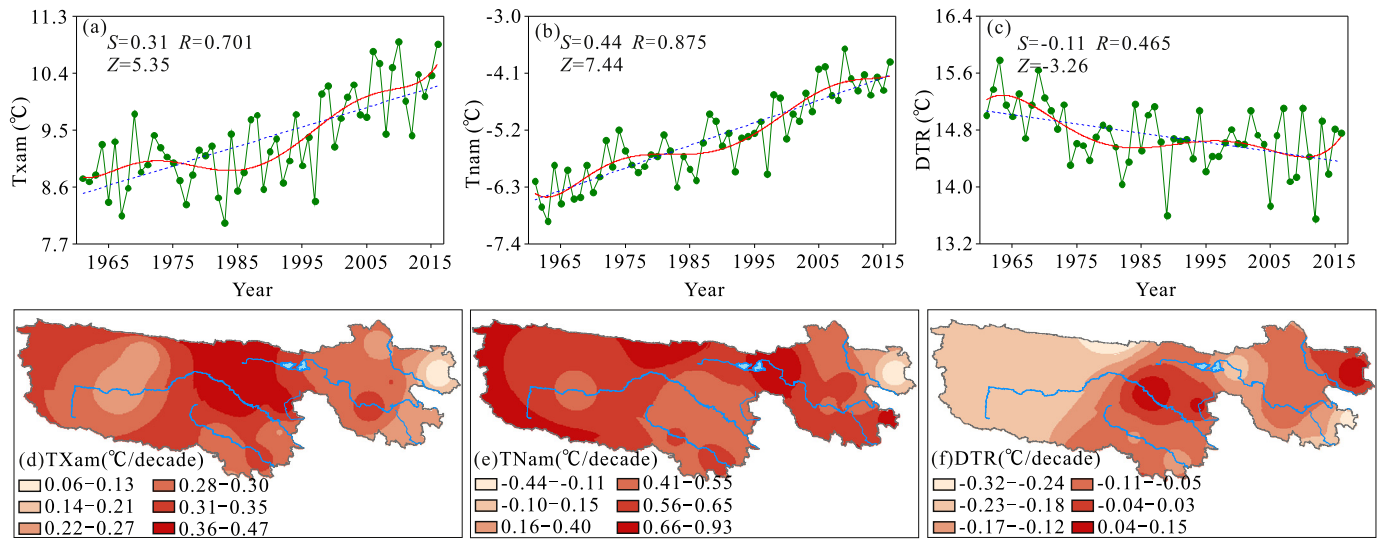


Fig. 2. The regional annual series and their spatial distribution patterns for TXam, TNam and the DTR in the Three River Headwaters region during 1961–2016.

data, such as precipitation, temperature, streamflow and water quality, in different parts of the world (Guo and Li, 2015; Zhang et al., 2017a). The value of the test statistic Z is used to compute the significance level; negative Z values indicate downward trends, whereas positive Z values indicate upward trends. A trend is significant at the 95% and 99% confidence levels if $|Z| > 1.96$ and $|Z| > 2.58$, respectively (Guo and Li, 2015). In addition, the nonparametric Sen's slope estimator is used to determine the magnitudes of the trends of regional annual average temperature extremes, and the annual slopes of the trends are converted into decadal slope values (Keggenhoff et al., 2015; Sen, 1968). Polynomial fitting is used to represent the interannual variations in the temperature extremes. Considering its simplicity and accuracy in interpolating meteorological variables, inverse distance weighting is used to draw maps in ArcGIS 10.5 showing the spatial distributions of the temperature extremes to analyze their spatial differences (Shi et al., 2016; Wang et al., 2013a).

2.4.2. Analysis of the relationships with atmospheric circulation patterns

To identify the factors that influence the temperature extremes, the correlations between the temperature extremes and the primary atmospheric circulation patterns on temperature extremes in the TRH are examined. Specifically, a Pearson's correlation analysis is performed between the temperature extremes and the atmospheric circulation patterns (Sun et al., 2016; You et al., 2010). The selected atmospheric circulation patterns are quantified in terms of the Arctic Oscillation index (AO), the North Atlantic Oscillation index (NAO), the Southern Oscillation Index (SOI) and the Western Pacific Subtropical High Intensity Index (WPI). Monthly mean values of these indices were obtained from the Earth System Research Laboratory (ESRL) of the Physical Sciences Division (PSD) of the United States' National Oceanic and Atmospheric Administration (NOAA) (<https://www.esrl.noaa.gov/psd/data/climateindices/list/>). A two-tailed version of Student's t -test is also used to calculate the statistical significance of the correlation coefficients at the 0.05 and 0.01 significance levels.

In this study, the regional averages of each temperature are calculated as the arithmetic means of the values at all of the selected stations. Winter, spring, summer and autumn are defined as extending from December to the following February (DJF), March to May (MAM), June to August (JJA) and September to November (SON), respectively.

3. Results

3.1. Temporal and spatial variations in the temperature extremes

3.1.1. Annual minimum and maximum temperatures and the diurnal temperature range (TXam, TNam, and DTR)

The annual series of annual mean maximum and minimum temperatures (TXam and TNam) and the diurnal temperature range (DTR) in the TRH region during 1961–2016 are shown in Fig. 2(a–c). The spatial distribution patterns of these extreme indices are shown in Fig. 2(d–f).

The TXam and TNam increased significantly in the TRH region from 1961 to 2016. The regional increasing trends for TXam and TNam are 0.31 ($P < 0.01$) and 0.44 ($P < 0.01$) °C/decade, respectively (Fig. 2a and b). For TXam and TNam, 100% (26/26) and 96% (25/26) of the stations, respectively, show significant increasing trends (Table 2). For TXam, the areas that experienced relatively large significant increases are mainly located in the northern and central portions of the TRH region (Fig. 2a). The relatively large significant increases in TNam over time are concentrated in the western and central portions of the region, as well as some scattered locations in the eastern portion of the region (Fig. 2b). In terms of the seasonal trends in TXam and TNam from 1961 to 2016, all of the seasons show marked increases; however, the increasing trend in the cold half of the year (autumn and winter) is larger than during the warm half of the year (spring and summer) (Table 3).

Over 1961–2016, the DTR decreased at a rate of 0.11 °C/decade ($P < 0.01$), and 54% (14/26) of the stations show significant decreasing trends (Table 2). The significant decreases over time are concentrated in the central and eastern portions of the region (Fig. 2c). Furthermore, in terms of the seasonal trend in the DTR from 1961 to 2016, all of the seasons show decreasing trends; however, only the trends associated with the spring and winter seasons are significant (Table 3).

3.1.2. Warm extremes (SU, TXx, TNx, TX90p, TN90p, and GSL)

The changes in the warm extremes during 1961–2016 are shown in Fig. 3(a, b, c, d, e and f). The spatial distribution patterns of these warm extremes are shown in Fig. 3(g–l).

During 1961–2016, the increasing trend in summer days (SU) is

Table 2

Regional decadal changes in the temperature extremes and the numbers of stations with statistically significant (S) (significant at the 0.05 level) temperature index trends.

Indices	Regional trend (range) (decade ⁻¹)	A decreasing trend (S)	An increasing trend (S)	No trend
TXam (°C)	0.31 ^b (0.06 to 0.55)	0 (0)	26 (26)	0
TNam (°C)	0.44 ^b (−0.45 to 1.34)	1 (1)	25 (25)	0
DTR (°C)	−0.11 ^b (−0.64 to 0.15)	20 (14)	6 (3)	0
SU (days)	1.2 ^b (−0.07 to 8.15)	2 (0)	19 (11)	5
TXx (°C)	0.39 ^b (0.13 to 0.62)	0 (0)	26 (23)	0
TNx (°C)	0.29 ^b (0.04 to 0.65)	0 (0)	26 (24)	0
TX90p (days)	3.05 ^b (1.06 to 5.17)	0 (0)	26 (26)	0
TN90p (days)	4.30 ^b (−0.62 to 7.31)	1 (0)	25 (25)	0
GSL (days)	3.94 ^b (−1.83 to 9.14)	1 (0)	25 (22)	0
ID (days)	−4.68 ^b (−10.22 to 1.85)	25 (24)	1 (0)	0
TX10p (days)	−2.47 ^b (−5.37 to 1.2)	25 (25)	1 (0)	0
TNn (°C)	0.49 ^b (−0.97 to 1.61)	2 (1)	24 (17)	0
TN10p (days)	−4.63 ^b (11.28 to 2.22)	25 (25)	1 (1)	0
TXn (°C)	0.26 ^a (−0.27 to 0.76)	3 (0)	23 (11)	0
FD (days)	−4.28 ^b (−8.35 to 1.95)	25 (25)	1 (0)	0

^a Significant at the 0.05 level (*t*-test).

^b Significant at the 0.01 level (*t*-test).

Table 3

The seasonal trends (°C/days per decade) for the temperature extremes that can be calculated seasonally.

Season	TXam	TNam	DTR	TXx	TNx	TX90p	TN90p	TX10p	TNn	TN10p	TXn
MAM	0.19 ^a	0.38 ^b	−0.19 ^b	0.13	0.33 ^b	1.49	3.58 ^b	−3.94 ^b	0.50 ^b	−1.67 ^b	0.16
JJA	0.28 ^b	0.39 ^b	−0.07	0.39 ^b	0.34 ^b	3.56 ^b	4.89 ^b	−4.40 ^b	0.45 ^b	−2.42 ^b	0.24 ^b
SON	0.34 ^b	0.44 ^b	−0.09	0.25 ^b	0.29 ^b	2.43 ^b	4.31 ^b	−4.67 ^b	0.56 ^b	−3.56 ^b	0.35 ^b
DJF	0.41 ^b	0.58 ^b	−0.11 ^a	0.53 ^b	0.58 ^b	4.02 ^b	3.60 ^b	−4.99 ^b	0.57 ^b	−2.40 ^b	0.25 ^b

^a Significant at the 0.05 level (*t*-test).

^b Significant at the 0.01 level (*t*-test).

1.2 days/decade ($P < 0.01$), and 42% (11/26) of the stations show significant increasing trends. However, from 2005 to 2016, the previously rapid increase slows and maintains a very high range (Table 2). The significant increases over time are concentrated in the northern parts of the region (Fig. 3g).

The highest daily maximum and minimum temperatures (TXx and TNx) increased significantly from 1961 to 2016. The regional trends in TXx and TNx are 0.39 ($P < 0.01$) and 0.29 ($P < 0.01$) °C/decade, respectively (Fig. 3b and c). In total, 88% (23/26) and 92% (24/26) of the stations show significant increasing trends for TXx and TNx, respectively (Table 2). The areas that display significant increases in TXx are mainly located in the central and eastern portions of the region (Fig. 3h). Significant increases in TNx over time are concentrated in the western portion of the region and occur in some scattered areas in the southern parts of the region (Fig. 3i). In terms of the seasonal trends in TXx and TNx from 1961 to 2016, all of the seasons exhibit significant increases, except for TXx in the spring. In addition, the greatest increasing trend is in winter.

The regionally averaged occurrences of warm days (TX90p) and nights (TN90p) increase significantly by 3.05 ($P < 0.01$) and 4.30 ($P < 0.01$) days/decade, respectively (Fig. 3d and e). All (26/26) of the stations display significant increasing trends for TX90p, and the areas that display relatively large significant increases are located primarily in the northern and central portions of the region, although a few stations with large significant increases are located in the eastern portion of the region (Fig. 3j). For TN90p, approximately 96% (25/26) of the stations show significant increases; these stations cover nearly the entire region, except for some of the eastern parts of the region (Fig. 3k). In terms of the seasonal trends in TX90p and TN90p from 1961 to 2016, all of the seasons show marked increases, except for TX90p in the spring. The seasonal variation in TX90p varies considerably, while the seasonal variation in TN90p is relatively consistent.

The growing season (GSL) in the TRH region increased in length at a rate of 3.94 days/decade ($P < 0.01$) from 1961 to 2016 (Fig. 3l).

Significant positive trends in the GSL occur at 85% (22/26) of the stations, and the rates of increase fall primarily between 4 and 9 days/decade.

3.1.3. Cold extremes (ID, TNn, TXn, TX10p, TN10p, and FD)

The regional changes in the cold extremes in the TRH region during 1961–2016 are shown in Fig. 4(a–f). The spatial variability in these cold indicators is shown in Fig. 4(g–l).

In contrast to the warm extremes, the numbers of ice days (ID) and frost days (FD) have decreased significantly in the TRH region during the past 56 years. The regional trends in the ID and FD are −4.68 ($P < 0.01$) and −4.28 ($P < 0.01$) days/decade, respectively, for 1961–2016 (Fig. 4a and f). The ID in most of the TRH region (92% of the stations) decreases significantly and follows trends that range primarily from −3 to −7 days/decade (Fig. 4g). Downward trends in the FD (−3 and −6 days/decade) occur over the entire region, except for several areas in the central and eastern portions of the TRH region (Fig. 4l).

The lowest daily minimum temperature (TNn) and the lowest daily maximum temperature (TXn) increase significantly from 1961 to 2016. The regional trends in TNn and TXn are 0.49 ($P < 0.01$) and 0.26 ($P < 0.01$) °C/decade, respectively (Fig. 4b and c). For TNn and TXn, 65% (17/26) and 42% (11/26) of the stations, respectively, show significant increasing trends (Table 2). For TNn, the areas that experience significant increases are located primarily in the northern and southwestern portions of the region, as well as some scattered areas in the southern portion of the region (Fig. 4h). The significant increases in TNx over time are concentrated in the northeastern portion of the region and some scattered areas in the northern and southeastern portions of the region (Fig. 4i). All of the seasons show marked increases in the seasonal trends in TXn and TNn from 1961 to 2016, and the increasing trend of TNn is larger than that of TXn in all seasons. Additionally, the increasing trends of TNn and TXn in autumn and winter are larger than those in spring and summer (Table 3).

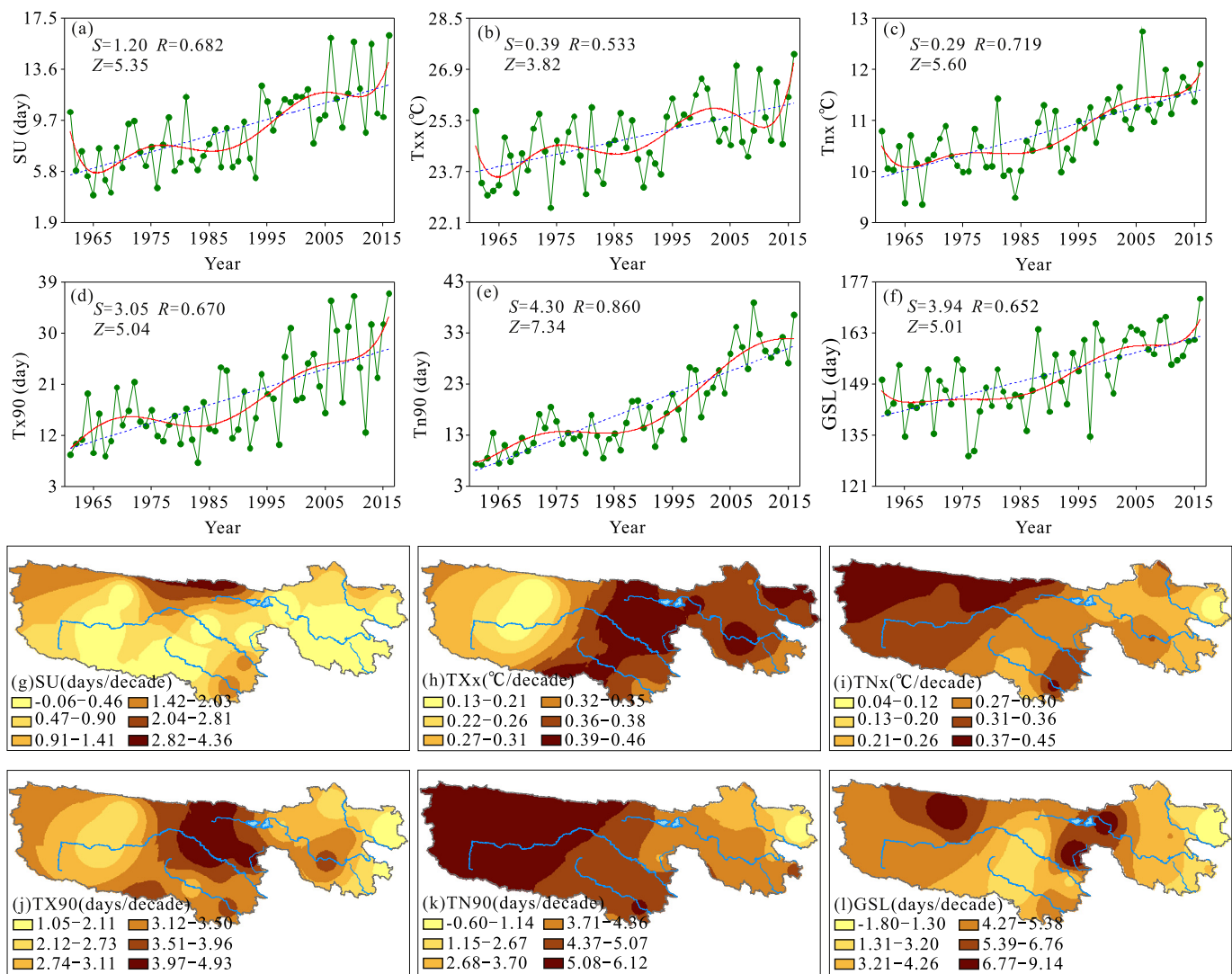


Fig. 3. The regional annual series and their spatial distribution patterns for the warm extremes (SU, TXx, TNx, TX90p, TN90p, and GSL) in the Three River Headwaters region during 1961–2016.

The relative indices of the cold extreme temperature events clearly vary across the TRH region (Fig. 4d and e, Fig. 4j and k). From 1961 to 2016, the occurrences of cold days (TX10p) and nights (TN10p) decrease significantly, by -2.47 ($P < 0.01$) and -4.63 ($P < 0.01$) days/decade, respectively (Fig. 4d and e). Approximately 96% (25/26) of the stations display significant decreases in both TX10p and TN10p during the past 56 years, and these stations cover nearly the entire TRH region (Table 2). The significant decreases in TX10p in most areas vary from -2 to -4 days/decade (Fig. 4j), whereas most of the stations with significant decreases in TN10p exhibit local rates that fall between -3 and -7 days/decade (Fig. 4k). All of the seasons show marked decreases in TX10p and TN10p, and the ranges of TX10p and TN10p in all of the seasons are -3.94 to -4.99 days/decade and -1.67 to -3.56 days/decade, respectively (Table 3).

3.2. Comparison of warm and cold extremes

To further understand the variations in the daily minimum and daily maximum temperatures, we also compare the relative magnitudes of the trends in the warm indices with those associated with the cold indices (Table 4). At approximately 92.3% of the stations, the trends of FD have larger magnitudes than those of SU. The statistical results show that approximately 88.5% of the stations have higher trend magnitudes

for ID than for SU. This result suggests that the winter temperatures increase more quickly than the summer temperatures. The regional trend for TX90p (3.05 days/decade) is much higher than that for TX10p (2.47 days/decade), and approximately 84.6% of the stations show larger trends for TX90p. A majority (53.8%) of the stations display higher trend magnitudes for TN10p than for TN90p; the regional trend for TN10p (4.63 days/decade) has a larger magnitude than that for TN90p (4.3 days/decade). Thus, during the day, there is a tendency towards increased interdiurnal variability.

The regional trend in the monthly TNn (0.49 °C/decade) is more than two times that of the monthly TNx (0.29 °C/decade). In addition, 34.6% of the stations display larger trend magnitudes for the monthly TXn than the monthly TXx. The above results indicate that most of the cold indices (TN10p, TXn, and TNn) display obviously higher warming trend magnitudes than the warm indices (TN90p, TXx, and TNx). In addition, the changes in the extreme indices based on the daily maximum temperature (TX10p and TX90p) are generally lower than changes in the extreme indices based on the daily minimum temperature (TN10p and TN90p). This result indicates that the warming trend magnitudes of the nighttime indices are clearly greater than those of the daytime indices.

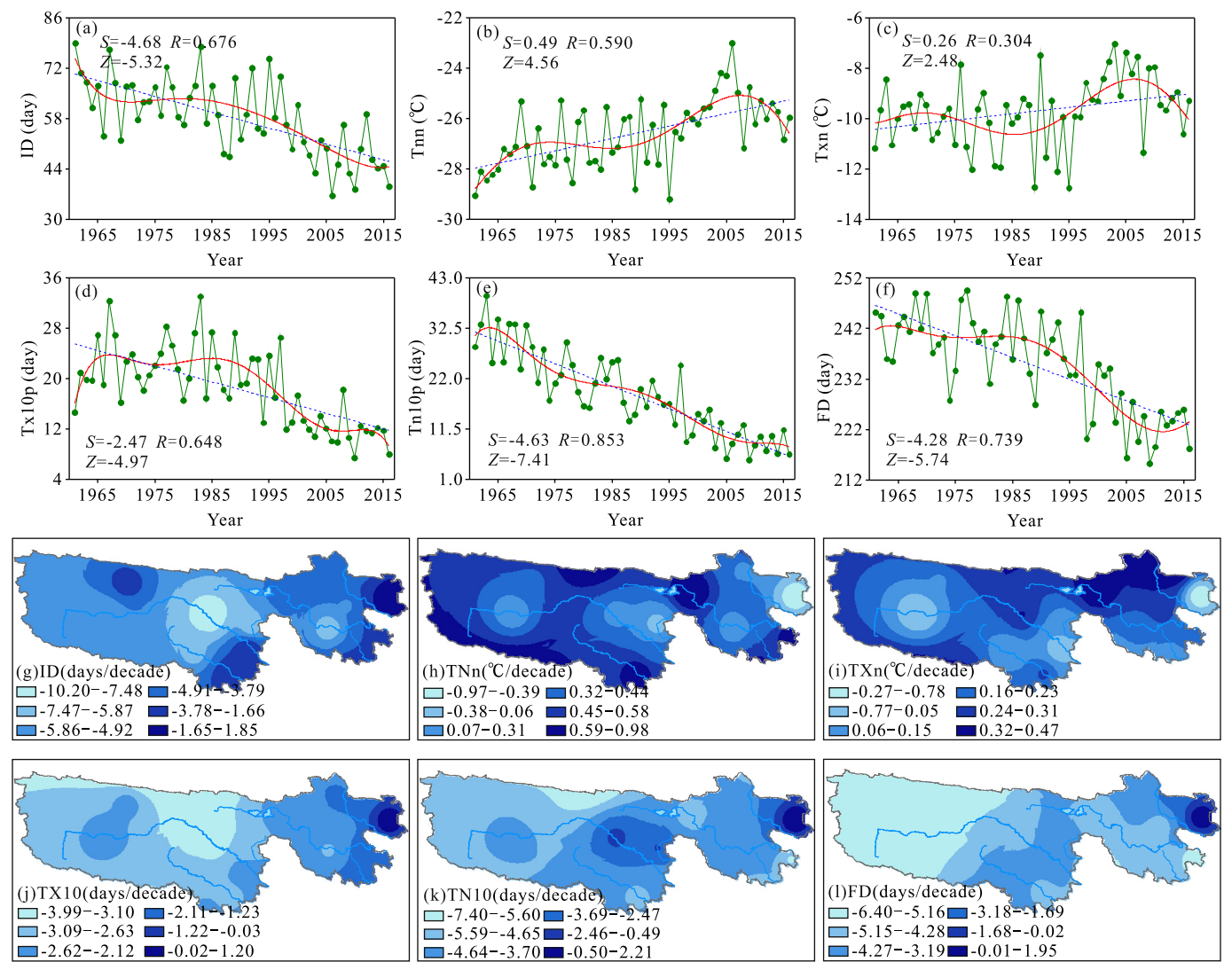


Fig. 4. The regional annual series and their spatial distribution pattern for the cold extremes (ID, TNn, TXn, TX10p, TN10p, and FD) in the Three River Headwaters region during 1961–2016.

Table 4
Numbers and proportions of individual stations where the trend in one index is greater in magnitude than the trend in a second index.

Indices	Comparison	Number	Proportion
FD > SU	Abs	24	92.3%
FD > GSL	Abs	18	69.2%
ID > SU	Abs	23	88.5%
TN90p > TX90p	Abs	21	80.8%
TN90p > TX10p	Abs	24	92.3%
TX90p > TX10p	Abs	22	84.6%
TN10p > TX10p	Abs	24	92.3%
TN10p > TX90p	Abs	22	84.6%
TN10p > TN90p	Abs	14	53.8%
TNn > TNx	Rel	16	61.5%
TNn > TXn	Rel	18	69.2%
TNx > TXx	Rel	8	30.8%
TXn > TXx	Rel	9	34.6%
TNam > TXam	Rel	23	88%

3.3. Correlation coefficients of temperature indices

To further clarify the interactions and relationships among the different temperature indices, Pearson correlation coefficients are calculated for the 15 extreme temperature indices and the mean temperature (Table 5). Except for the DTR, both the warm and cold extremes are highly correlated with the mean annual temperature, and most of the indices display correlation coefficients that exceed 0.57 ($P < 0.01$). The warm temperature indices are positively correlated with the mean temperature, with correlation coefficients ranging from 0.57 to 0.95. TN90p display the strongest correlation with the mean temperature, with a correlation coefficient of 0.95. The cold indices, except for TNn and TXn, are positively correlated with the mean temperature; the negative correlations between the mean temperature and the other cold indicators are also significant, with correlation coefficients ranging from -0.84 to -0.91 . In addition, there are positive relationships among the warm indices, and the cold indices other than TNn and TXn also display positive relationships. However, negative correlations are

Table 5
The correlation matrix for the regionally averaged extreme temperature indices.

	Index	Tmean	TXam	TNam	DTR	SU	TXx	TNx	TX90p	TN90p	GSL	ID	TX10p	TN10p	FD	TNn
Indices	Tmean	1														
	TXam	0.95 ^b	1													
	TNam	0.96 ^b	0.83 ^b	1												
	DTR	−0.22	0.08	−0.48 ^b	1											
Warm indices	SU	0.74 ^b	0.74 ^b	0.68 ^b	−0.06	1										
	TXx	0.57 ^b	0.56 ^b	0.52 ^b	−0.04	0.86 ^b	1									
	TNx	0.75 ^b	0.68 ^b	0.76 ^b	−0.29 ^a	0.82 ^b	0.73 ^b	1								
	TX90p	0.89 ^b	0.95 ^b	0.78 ^b	0.11	0.76 ^b	0.63 ^b	0.68 ^b	1							
	TN90p	0.95 ^b	0.86 ^b	0.96 ^b	−0.38 ^b	0.74 ^b	0.54 ^b	0.79 ^b	0.83 ^b	1						
	GSL	0.85 ^b	0.80 ^b	0.82 ^b	−0.20	0.65 ^b	0.46 ^b	0.60 ^b	0.76 ^b	0.80 ^b	1					
Cold indices	ID	−0.88 ^b	−0.92 ^b	−0.78 ^b	−0.05	−0.57 ^b	−0.40 ^b	−0.59 ^b	−0.85 ^b	−0.77 ^b	−0.64 ^b	1				
	TX10p	−0.88 ^b	−0.93 ^b	−0.77 ^b	−0.08	−0.70 ^b	−0.52 ^b	−0.63 ^b	−0.79 ^b	−0.77 ^b	−0.75 ^b	0.83 ^b	1			
	TN10p	−0.91 ^b	−0.77 ^b	−0.96 ^b	0.49 ^b	−0.65 ^b	−0.53 ^b	−0.71 ^b	−0.69 ^b	−0.87 ^b	−0.80 ^b	0.72 ^b	0.76 ^b	1		
	FD	−0.84 ^b	−0.74 ^b	−0.87 ^b	0.40 ^b	−0.63 ^b	−0.40 ^b	−0.65 ^b	−0.70 ^b	−0.90 ^b	−0.86 ^b	0.60 ^b	0.68 ^b	0.81 ^b	1	
	TNn	0.67 ^b	0.67 ^b	0.61 ^b	−0.05	0.40 ^b	0.27 ^a	0.38 ^b	0.55 ^b	0.57 ^b	0.43 ^b	−0.76 ^b	−0.65 ^b	−0.59 ^b	−0.40 ^b	1
	TXn	0.44 ^b	0.54 ^b	0.34 ^a	0.25	0.26	0.10	0.23	0.39 ^b	0.37 ^b	0.26	−0.61 ^b	−0.60 ^b	−0.31 ^a	−0.32 ^a	0.77 ^b

^a Significant at the 0.05 level.

^b Significant at the 0.01 level.

found between the warm and cold indices. In addition, TXam and TNam exhibit the same relationships with the warm and cold extreme indices as the mean temperature.

3.4. Abrupt change analysis

The M-K test is used to detect abrupt changes in the temperature extremes, and the cumulative deviation and moving *t*-test methods are both used to analyze the timing of the abrupt changes. The results indicate that, during the last 56 years, most of the temperature extremes display abrupt changes (Fig. 5), and the results of the three different methods for determining the timing of the abrupt changes are relatively consistent with each other (Table 6). TXam shows an abrupt change in 1998, when it jumps from a relatively cold period to a relatively warm period. The DTR displays an abrupt change in approximately 1972, when its declining trend increases further. Most of the cold and warm extremes display abrupt changes after the 1990s, with the exception of TNn, which displays an abrupt change from a period with lower temperatures to one with higher temperatures in 1986, consistent with the arid region of China (Chen et al., 2014).

4. Discussion

Extreme weather events have increased in frequency and have become more severe due to global warming. For example, the frequencies of warm days and warm nights have increased, and the frequencies of cold days and cold nights have decreased (IPCC, 2013). In addition, many simulations of future climate events also indicate that a warming climate will result in many extreme weather events (Dong et al., 2016; Meehl et al., 2016; Zhang et al., 2017b). Using 15 extreme temperature indices, this study analyzes the spatial distributions and temporal variations of extreme temperature events in the TRH region over the past 56 years. At a majority of the stations, significant increases are detected in the warm extremes, such as SU, TXx, TNx, TX90p, TN90p, and GSL, and in the annual mean extremes, such as TXam and TNam, from 1961 to 2016. The cold extremes, including TX10p, TN10p, TN90p, FD, ID and the DTR, show statistically significant decreases at most of the stations. Moreover, significant increases in TNn and TXn are also observed. The changes in extreme weather events in the TRH region are broadly similar to those seen in many other regions in terms of their responses to the recent global warming (Alexander et al., 2006). However, the variation in the extreme indices of the TRH region is significantly greater than that in China as a whole (You et al., 2010) and at the global scale (Alexander et al., 2006). Therefore, the TRH region is sensitive to global warming, as manifested by extreme temperature

events. Compared with the surrounding portions of the Tibetan Plateau, the trend magnitudes of the warm extremes within the TRH region, except for GSL, are significantly higher than those of the central and eastern parts of the Tibetan Plateau (You et al., 2008a) and southwestern China (Li et al., 2012b); however, they are lower than those observed in the northwestern arid region of China (Chen et al., 2014). The trend magnitudes of the cold extremes are lower than those of the central and eastern parts of the Tibetan Plateau (You et al., 2008a); however, they are higher than those observed in southwestern China and the northwestern arid region of China (Li et al., 2012b; Wang et al., 2013a). Additionally, for most seasons, the magnitudes of the variations in the temperature extremes in autumn and winter are significantly higher than those in spring and summer, which is consistent with results for the Loess Plateau of China (Wang et al., 2017). However, the warming magnitudes of the temperature extremes in winter within the TRH region are significantly higher than those observed on the Loess Plateau, especially for the cold extremes.

A comparative analysis of the cold and warm temperature extremes suggests that the warming amplitudes of most of the cold indices (TNam, ID, TNn, TN10p, and FD) are significantly higher than those of the warm indices (TXam, SU, TXx, TN90p, and GSL), mainly because the magnitude of warming is greater in winter than in summer. The physical mechanism for this difference is that the water vapor content in the air is lower in winter than in summer (IPCC, 2013); thus, the radiative forcing effect of greenhouse gases is relatively high in the winter, which in turn causes greater warming. Meanwhile, the warming rates of the nighttime indices (TN90 and TN10) are also significantly larger than those of the daytime indices (TX90 and TX10). Numerous studies performed in other regions also confirm that the warming magnitudes of the cold temperature extremes are greater than that of the warm temperature extremes, and the warming rates of the nighttime indices are larger than those of the daytime indices (Alexander et al., 2006; Li et al., 2012b; Ruml et al., 2017). The polynomial curve of the temperature extremes shows that the warming magnitudes of most of the indices are more evident after the 1990s than before the 1990s. This result is further confirmed by the abrupt change analysis performed using the M-K test (Fig. 5), which indicates that most of the temperature extremes display abrupt changes after the 1990s in the TRH region. However, the warming magnitudes of the cold temperature extremes (ID, TNn, TN10p, and FD) and the nighttime indices are more evident after the abrupt changes than before, which indicate that changes in the temperature extremes in response to the hiatus in global warming are not obvious. This result is consistent with a study showing that temperature extremes have persisted at high levels after the hiatus in global warming (Seneviratne et al., 2014). The above analysis shows

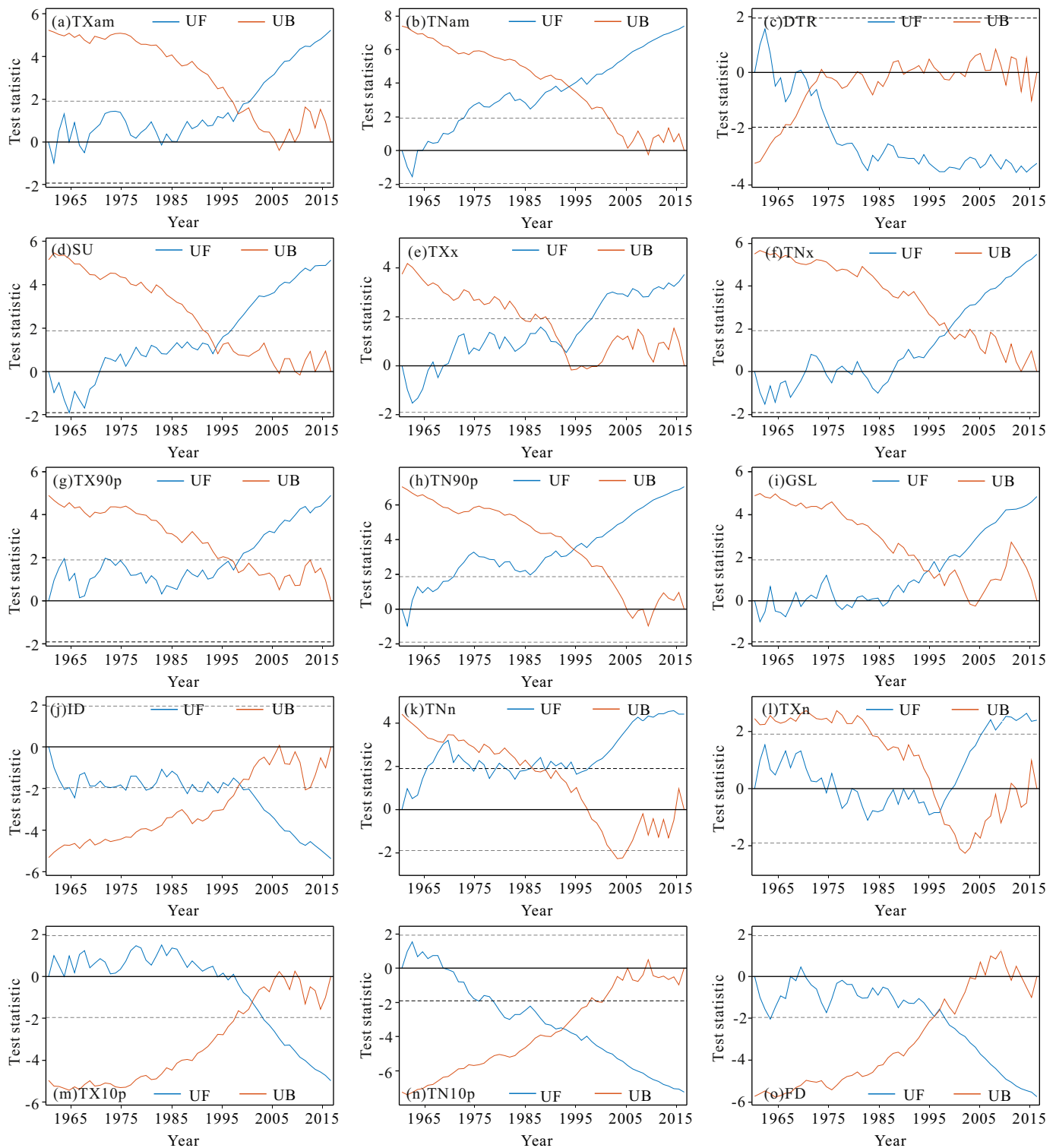


Fig. 5. Abrupt change analysis for the regionally averaged extreme temperature indices.

that, since the 1990s, the overall temperature increase in the TRH region has been more evident at night than during the day and more evident in winter than in other seasons. This pattern of change may be related to the frequent occurrence of warm winter events (IPCC, 2013; Alexander et al., 2006).

Given the increase in frequency of extreme climate events, the social economy, environment, ecosystems and human health have all been affected to some degree. Thus, the causes of extreme climate events

have gradually become a major topic of research for many scholars. The above analysis of the temperature extremes in the TRH region and in other regions indicates that most of the cold indices are higher than those in the northwestern arid regions of China, the Loess Plateau and the Tibetan Plateau as a whole, whereas the variations in the warm indices are relatively complex.

Li et al. (2012a) studied the extreme temperature changes in southwestern China and showed that altitude and latitude are

Table 6

Abrupt change analysis for the regionally averaged extreme temperature indices using difference methods.

Indices	Year of change		
	Mann-Kendall	Cumulative deviation	Moving <i>t</i> -test
TXam	1998 ^a	1998 ^a	1997 ^a
TNam	1993	1998 ^a	1997 ^a
DTR	1972 ^a	1973 ^a	1973 ^a
SU	1993 ^a	1993 ^a	1993 ^a
TXx	1992 ^a	1993 ^a	1993 ^a
TNx	1999 ^a	1994 ^a	1994 ^a
TX90p	1998 ^a	1998 ^a	1997 ^a
TN90p	1994	1997 ^a	1997 ^a
GSL	1995 ^a	1993 ^a	1993 ^a
ID	1998 ^a	1997 ^a	1997 ^a
TNn	1986	1998 ^a	1997 ^a
TXn	1997 ^a	1997 ^a	1997 ^a
TX10p	2001 ^a	1997 ^a	1997 ^a
TN10p	1992	1986 ^a	1986 ^a
FD	1996 ^a	1997 ^a	1997 ^a

^a Significant at the 0.05 level.

important factors that influence regional climate changes. Pepin and Seidel (2005) studied the range of temperature variability within different terrain types on a global scale and showed that temperatures at sites in mountainous regions display smaller warming trends compared to other types of sites; that is, there is a significant negative relationship between altitude and temperature change. Li et al. (2012a) showed that, due to the large number of degrees of freedom in air, the warming trends in temperature indices at sites on plains are higher than those within mountainous areas. An analysis of the correlations of the temperature extremes within the TRH region with longitude, latitude and altitude indicates that the correlations of the indices with altitude are not obvious, with the exception of the significant negative correlation between the DTR and altitude. Moreover, correlations of longitude and latitude with most of the indices are also not evident, indicating that the temperature extremes within the TRH are not affected by latitude, longitude or altitude (Table 6). You et al. (2008b) studied the correlations of the temperature extremes within the central and eastern portions of the Tibetan Plateau with latitude, longitude and altitude and arrived at the same result. The reason may be that the TRH region is located within the northeastern portion of the Tibetan Plateau, where the average altitude is above 4000 m; thus, the response of the magnitudes of the variations in the temperature extremes to global warming is not obvious (Table 7). Meanwhile, the terrain of the TRH is quite complex, and the atmospheric circulation patterns also have a significant influence; all of these factors result in this phenomenon.

The variations in the extreme temperature indices and the seasonal atmospheric circulation indices are closely related. Specifically, extreme temperatures are caused by anomalous atmospheric circulation disturbances, which provide a climatic background for daily extreme events (Martin et al., 2003; You et al., 2010; Zhong et al., 2017). From the perspective of climate statistics, extreme temperature events are closely linked to seasonal averages (Fig. 6).

In this study, in summer, the WPI is negatively correlated with all of

the warm temperature extremes but is positively correlated with most of the cold temperature extremes, except for TNn and TXn. In winter, the WPI is positively correlated with TNx, TX90p, TN90p and TNn but is negatively correlated with ID and TN10p. The WPI, which affects almost one-quarter of the Northern Hemisphere in summer, represents a large-scale anticyclonic circulation that has been identified as one of the dominant components of the East Asian summer monsoon system (Huang et al., 2015). These results indicate that the WPI strongly influences temperature extremes in the TRH region in summer; that is, the East Asian summer monsoon system has a significant influence on the temperature extremes of the TRH region, but the WPI has a weak influence on temperature extremes in winter. In addition to the WPI, the NAO in summer is negatively correlated with most of the warm temperature extremes but is positively correlated with the cold temperature extremes, except for TNn and TXn. In winter, the NAO is positively correlated with most of the warm temperature extremes but is negatively correlated with ID, TX10p, TN10p and FD. These results indicate that, in summer, the NAO strongly influences temperature extremes in the TRH region. The AO is a major factor that controls Northern Hemisphere climate variability, and it is also correlated with the strength of the East Asian winter monsoon and the Siberian high-pressure system (Chen et al., 2014; Thompson and Wallace, 1998). In this study, only the winter AO index displays a weak but significant correlation with some of the extreme temperature indices (SU, TNx, GSL, TN10p, and FD), which indicates that the East Asian Winter Monsoon and the Siberian high-pressure system have weak effects on temperature extremes. The SOI is an important descriptor of the El Niño-Southern Oscillation (ENSO) phenomenon. Previous studies have shown that the ENSO index has a limited impact on temperatures in China but that it drives changes in precipitation in most parts of China. In this study, the SOI displays almost no significant correlation with any of the temperature extremes, further indicating that the SOI has almost no effect on the temperature extremes in the TRH region. These results suggest that the decreasing trends in winter cold temperature extremes and the increasing trends in winter warm temperature extremes are closely related to circulation changes (You et al., 2011).

5. Conclusions

The understanding of regional temperature extremes in terms of spatiotemporal trends is extraordinarily important, owing to the huge impact of temperature extremes on the environment and society. In this study, a comprehensive and up-to-date analysis of temperature extremes over the TRH region on the Tibetan Plateau is conducted for the period of 1961–2016 using 15 temperature indices calculated using data from 26 stations, and the results are then related to 4 atmospheric circulation indices. All of the warm extremes (SU, TXx, TNx, TX90p, TN90p, and GSL) display significant increasing trends over the TRH region during 1961–2016. Many of the cold extremes, including ID, TX10p, TN10p, and FD, show decreasing trends during the same period; however, TNn and TXn show increasing trends. In addition, the annual minimum and maximum temperature indices (TXam and TNam) show significant increasing trends, and the diurnal temperature range (DTR) shows a significant decrease from 1961 to 2016. Most of the seasonal warm and cold temperature extremes, including TXam, TNam, DTR,

Table 7

Correlations between the extreme temperature trends and longitude, latitude and altitude in the TRH region.

Indices	TXam	TNam	DTR	SU	TXx	TNx	TX90p	TN90p	GSL	ID	TX10p	TNn	TN10p	TXn	FD
Altitude	−0.19	0.03	−0.69 ^b	−0.25	−0.20	0.30	−0.35	−0.29	−0.27	−0.06	0.10	−0.17	0.24	−0.01	0.16
Latitude	0.33	0.02	0.54 ^b	−0.17	0.05	0.10	0.15	0.29	0.38	−0.12	−0.24	0.21	−0.21	0.05	−0.11
Longitude	−0.33	−0.31	−0.15	0.32	0.42 ^a	−0.35	0.17	−0.09	−0.31	−0.29	0.49 ^a	−0.33	0.25	−0.56 ^b	−0.38

^a Significant at the 0.05 level (*t*-test).

^b Significant at the 0.01 level (*t*-test).

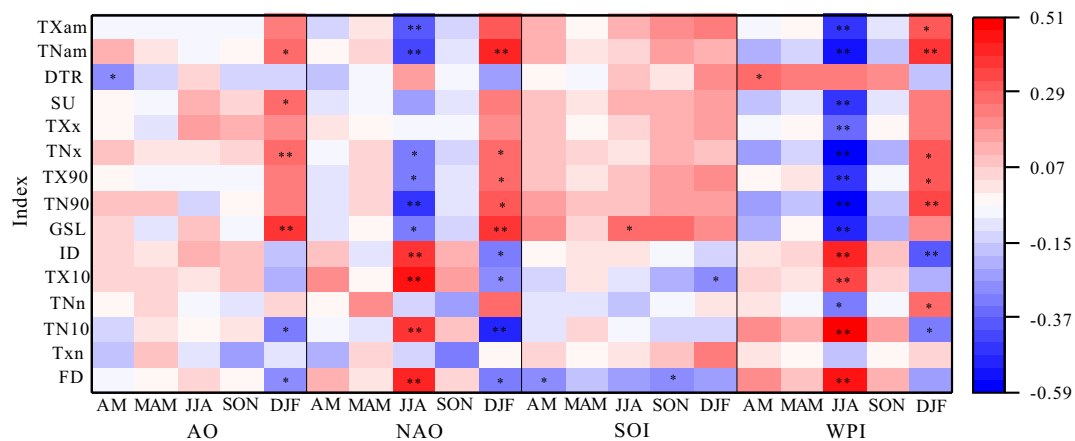


Fig. 6. Correlation coefficients between the regionally averaged extreme temperature indices and the atmospheric circulation indices.

TXx, TNx, TX90p, TN90p, TX10p, TN10p, TNn, and Txn, display significant increases or decreases in all seasons, and a high proportion of the indices are lower during the warm half of the year than during the cold half of the year. Furthermore, most of the temperature extremes display the largest trend magnitudes in winter. Meanwhile, comparison of the warm and cold extremes indicates that the warming trend magnitudes of most of the cold indices are obviously higher than those of the warm indices and that the warming trend magnitudes of the nighttime indices are obviously greater than those of the daytime indices, mainly because the magnitude of warming is greater in winter than in summer. Most of these findings are consistent with those of many previous regional studies. From a spatial perspective, increasing or decreasing trends in the temperature extremes are found at most of the stations, but the change magnitude varies among the different regions. The abrupt change analysis performed using the M-K test indicates that, during the past 56 years, most of the temperature extremes display abrupt changes, mainly in the 1990s. A correlation analysis of the temperature extremes of the TRH with longitude, latitude and altitude indicates that the temperature extremes of the TRH are hardly affected by latitude, longitude or altitude. This lack of influence may occur because the TRH region is located on the Tibetan Plateau, where the average altitude is above 4000 m and the terrain is quite complex. Moreover, the response of the magnitudes of the variations in the temperature extremes to global warming is not obvious, and the atmospheric circulation patterns also have a significant influence. The variations in the temperature extremes and the seasonal atmospheric circulation indices are closely related; for example, the NAO and WPI in summer display prominent correlations with most of the temperature extremes, and the NAO and WPI display prominent correlations with some of the temperature extremes in winter. Furthermore, in winter, the AO displays a prominent correlation with several of the extreme temperature indices. All of these results indicate that atmospheric circulation patterns have a remarkable impact on temperature extremes in summer and winter.

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